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Internal mechanical work and maximum subtalar joint pronation in different gradients

Trabalho mecânico interno e máxima pronação subtalar em diferentes gradientes de inclinação

Trabajo mecánico interno y máxima pronación subtalar en diferentes gradientes de inclinación

Karina Azevedo Lopes[a], Mayara Maciel Batista [a, b], Letícia Martins [a],
André Luiz Kiihn [a], Marcos Roberto Queiroga [a], Marcus Peikriszwili Tartaruga [a, b]*

[a] Universidade Estadual do Centro-Oeste do Paraná (UNICENTRO), Guarapuava, PR, Brazil
[b] Universidade Federal do Paraná (UFPR), Curitiba, PR, Brazil

Abstract

Introduction: Some authors have described the importance of physiological intensity in the behavior of the biomechanical aspects of running (for example, subtalar pronation), but the complex relationships between these variables are not yet well understood. **Objective:** This study investigated the influence of positive gradients on internal mechanical work (W_{int}) and maximum subtalar pronation at a submaximal

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* KAL: undergrad, e-mail: karinalopes93@hotmail.com
MMB: Master's student, e-mail: mayamb2@hotmail.com
LM: undergrad, e-mail: leticia_marttins@hotmail.com
ALK: undergrad, e-mail: andrekiihn@gmail.com
MRQ: PhD, e-mail: queirogamr@hotmail.com
MPT: PhD, e-mail: mtartaruga@unicentro.br

running speed. **Method**: Sixteen male, trained long-distance runners (age: 29 ± 7 yr; stature: 1.72 ± 0.07 m; body mass: 72.1 ± 10.6 kg), performed four running economy tests (gradients: +1%, +5%, +10% and +15%, respectively) for four minutes at a same submaximal running speed to quantify the maximum values of subtalar pronation and predict the W_{int} values. Data were analyzed using descriptive statistics, Student's T-test, and one-way repeated-measures (ANOVA) along with the Statistical Package for the Social Sciences (SPSS) version 20.0. **Results**: W_{int} increased according to the gradient ($p < 0.05$). However, no significant differences were observed in the maximum values of maximum subtalar pronation corresponding to each gradient. **Conclusion**: Results show the maximum subtalar pronation during submaximal running depends on the speed rather than intensity of effort.

Keywords: Ankle Injuries. Exercise Test. Mechanical Stress. Running.

Resumo

***Introdução**: Autores têm descrito a importância da intensidade fisiológica no comportamento dos aspectos biomecânicos da corrida (por exemplo, a pronação subtalar), mas as complexas relações entre essas variáveis todavia não estão bem compreendidas. **Objetivo**: O presente estudo investigou a influência de gradientes de inclinação positivos, a uma mesma velocidade de corrida, no trabalho mecânico interno (W_{int}) e na máxima pronação subtalar. **Método**: Dezesseis corredores masculinos, especialistas em longas-distâncias (idade: 29 ± 7 anos; estatura: 1,72 ± 0,07 m; massa corporal: 72,1 ± 10,6 kg) realizaram quatro testes de economia de corrida (gradientes: +1%, +5%, +10% e +15%, respectivamente), de quatro minutos cada, em uma mesma velocidade submáxima de corrida, objetivando quantificar os valores de máxima pronação subtalar e predizer os W_{int}. Foi realizada a análise descritiva e aplicados os testes T de Students e ANOVA de Medidas Repetidas, todos através do software Statistical Package for the Social Sciences (SPSS), versão 20.0. **Resultados**: O W_{int} aumentou com o gradiente ($p < 0,05$). Entretanto, diferenças estatisticamente significativas não foram observadas nos valores de máxima pronação subtalar correspondentes a cada gradiente. **Conclusão**: Os resultados do presente estudo revelam que a máxima pronação subtalar durante a corrida submáxima é dependente da velocidade em comparação a intensidade de esforço.*

***Palavras-chave**: Traumatismo do Tornozelo. Teste de Esforço. Estresse Mecânico. Corrida.*

Resumen

***Introducción**: Autores tienen descrito la importancia de la intensidad fisiológica en el comportamiento de los aspectos biomecánicos de la carrera (por ejemplo, la pronación subtalar), mas las complejas relaciones entre esas variables todavía no están bien comprendidas. **Objetivo**: El presente estudio investigó la influencia de gradientes de inclinación positivos, a una misma velocidad de carrera, en el trabajo mecánico interno (W_{int}) y en la máxima pronación subtalar. **Método**: Dieciséis corredores masculinos, especialistas en largas-distancias (edad: 29 ± 7 años; estatura: 1,72 ± 0,07 m; masa corporal: 72,1 ± 10,6 kg) realizaron cuatro testes de economía de carrera (gradientes: +1%, +5%, +10% e +15%, respectivamente), de cuatro minutos cada, en una misma velocidad submáxima de carrera, objetivando cuantificar los valores de máxima pronación subtalar y predecir los W_{int}. Fue realizada la análisis descriptiva y aplicados los testes T de Students y ANOVA de Medidas Repetidas, todos realizados en el software Statistical Package for the Social Sciences (SPSS), versión 20.0. **Resultados**: EL W_{int} aumentó con el gradiente ($p < 0,05$). Entretanto, diferencias estadísticamente significativas no fueran observadas en los valores de máxima pronación subtalar correspondientes a cada gradiente. **Conclusión**: Los resultados del presente estudio revelan que la máxima pronación subtalar durante la carrera submáxima es dependiente de la velocidad en comparación a la intensidad del esfuerzo.*

***Palabras clave**: Traumatismo del Tobillo. Prueba de Esfuerzo. Estrés Mecánico. Carrera.*

Introduction

In recent decades, the study of the human gait has gained importance in sport and rehabilitation research centers [1]. Numerous studies investigated the relationship between physical activity and injuries, particularly those related to running [2, 3]. Researches associating the behavior of the subtalar joint angle, specifically subtalar pronation, with the footwear used for running have significantly contributed to the comprehension of injuries involving the hip, knee, ankle and foot [4].

Subtalar pronation consists of an impact-absorbing mechanism, which acts combined with other body mechanisms to decrease the tension in some articular structures with an adequate level of impact and without provoking microtraumas. However, pronation becomes pathological when it exceeds its physiological articular range of motion, that is, when the maximum subtalar pronation exceeds approximately 12º. This state is known as hyperpronation [5]. Maximum subtalar pronation is generally reached between 20% and 40% of the stance phase, and is mainly influenced by the linear speed of running, intensity of effort, muscle imbalance and/or ligament laxity, and the running technique used by the runner [6]. Maximum subtalar pronation during running contributes to running-related injuries. However, complex relationships between joint motion and running technique are not well understood [7].

Margaria [8], in the first study reporting the metabolic optimum walking gradient, found the energetic cost of running is minimized at a gradient of approximately -10% (Margaria et al. [9]). Margaria's technique for calculating the efficiency of locomotion linked the metabolic energy consumption to the estimated mechanical work and the running technique. Davies et al. [10] used similar methods. The authors measured the energetics of human running and estimated the mechanical work by considering only the work done to lift and lower the body's center of mass.

Traditionally, the human locomotion mechanics have been analyzed according to the mechanical work performed [11]. The total locomotion mechanical work (W_{tot}) is conventionally considered the sum of the two separate aspects of mechanical work: external mechanical work (W_{ext}) and internal mechanical work (W_{int}) [12]. W_{int} represents the work required to accelerate the limbs reciprocally with the body's center of mass during human locomotion. It is computed using both segment movements and anthropometric parameters [13]. In contrast, W_{ext} represents the work required to lift and accelerate the body's center of mass within the environment. W_{ext} has been investigated in various conditions, such as force platform and kinematic analysis, and across many different populations [12]. For example, Buczek and Cavanagh [14] used a force platform installed along a 17 m downhill walkway to measure the power of the knee and ankle joints at a gradient of approximately -8%. However, Iversen and McMahon [15] first developed a model capable of predicting the pattern of motion of gradient running and demonstrated a probable relationship between these two variables.

The literature reveals two key mathematical models to determine the maximum subtalar pronation. The first model uses two reference points, both located in the subject's shoe: marker 1 (M1), located on the lower edge of the shoe above the sole, and marker 2 (M2), located at the center of the upper edge of the shoe, above the Achilles tendon. In this model, the maximum subtalar pronation can be determined by the maximum angle formed between the segment M1-M2 (S1) and the vertical axis y, or between the S1 and the axis parallel to the shoe sole (Ferrandis et al. [16]). The second model uses four reference points: markers M1 and M2 (as in the previous model), marker 3 (M3), located at the origin of the Achilles tendon (calcaneal tendon), and marker 4 (M4), located at the origin of the Gastrocnemius muscle. In this model, the maximum subtalar pronation is determined by the maximum angle formed between the segments S1 and S2 (M3-M4) (see Wit et al. [17]).

Although some studies have examined the influence of positive gradients on mechanical work and maximum subtalar pronation, a literature review has revealed that little research has investigated the effect of effort intensity on these dependent variables. This study intends to address this gap by investigating the influence of positive gradients on W_{int} and maximum subtalar pronation at a submaximal running speed.

Methods

Subjects. Sixteen male, trained long-distance runners (age: 29 ± 7 yr; stature: 1.72 ± 0.07 m; body mass: 72.1 ± 10.6 kg), were recruited. The sample size was calculated according to a previous study by Williams and Cavanagh [18] investigating the relationship between distance running mechanics, running economy (RE) and performance. The sample size had a statistical power of 80% and significance of $p \leq 0.05$. The mean maximal oxygen uptake of the subjects (VO_{2max}) was 50.6 ± 4.9 $mL \cdot kg^{-1} \cdot min^{-1}$. The subjects had a mean of 3.4 ± 1.4 yr of running practice, and their usual racing distance ranged from 10 km to 45 km. The experimental group typically ran 3-5 $d \cdot wk^{-1}$ with a mean weekly running distance of 40 ± 10 $km \cdot wk^{-1}$ during the month preceding the investigation. The subjects provided their informed consent to participate in the study. The study was conducted according to the Declaration of Helsinki. A local ethics committee for protection of individuals approved the project before its commencement (CAAE: 70903716.1.0000.0106).

Experimental design. Subjects underwent two laboratory sessions: (1) sample characterization; and (2) four submaximal treadmill tests (RE). Due to the influence of the environment on physiological processes that contribute to the regulation of metabolic rate and neuromuscular responses, the laboratory ambient temperature (± 25°C) and relative humidity (± 55%) were controlled according to ISO-8573-1 (international standards). Some restrictions were imposed on the subjects: (a) no food and drink at least 3 to 4 hrs before the tests; (b) no stimulants or intense physical activity 12 hrs before the evaluation; and (c) use of their own training shoes (with rubber soles and no cleats). Sports shoes and anti-pronation shoes were not allowed.

Session 1: Sample Characterization. Anthropometric parameters were recorded using scales and stadiometer (WELMY-110, Santa Bárbara d'Oeste, SP, Brazil) and a skinfold caliper (LANGE SKINFOLD CALIPER-C130, Porto Alegre, RS, Brazil). The body fat percentage was calculated using the Siri equation [19]. Body density was calculated using the Jackson and Pollock method [20]. A professional with experience in anthropometric evaluations performed all measurements. After the anthropometric measurements were taken, each subject performed a maximal test on a motorized treadmill (Movement-RT350, Pompeia, Brazil) to determine VO_{2max}, proposed by Ellestad et al. [21].

Session 2: Running Economy Tests. Initially, four reflective points were affixed to each leg. Two contrasting markers were placed on the midline of the heel counter of the shoe and two on the lower leg midline. See Figure 1 (cited by Wit et al. [17]).

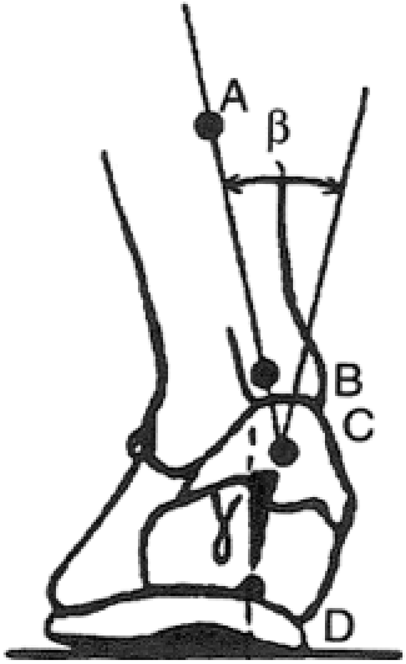

Figure 1 – Illustration of the markers at the rear part of the left leg and foot.

After the preparation phase, the treadmill was turned on, and the subjects completed a three-minute warm-up consisting of walking at a comfortable speed. Then, subjects increased the speed to their optimal running speed, corresponding to the intensity of lower energy expenditure and better performance in long-distance running. This was maintained for four minutes on the gradients used in this study (+1%, +5%, +10% and +15%), with a five-minute rest period between conditions. To quantify the maximum values of subtalar pronation, each running test was filmed at the posterior frontal plane at a sampling frequency of 240 Hz using a high-speed camera (Casio Exilim EX-FH25, Japan). The camera was mounted on a tripod, placed 2 m from the treadmill, and aligned so that the plane of the camera was parallel to the treadmill. Three consecutive steps were averaged during the last 15 seconds of each RE test. The kinematic records were scanned manually and automatically using DVIDEO software (UNICAMP, Campinas, SP, Brazil). Then these records were used to determine the W_{int} and maximum values of subtalar pronation using two routines developed using the MATLAB software (R2017a, MathWork, Natick/ Massachusetts, United States) according to the two mathematical models discussed by Tartaruga et al. [2], using a fifth-order Band-Pass Butterworth filter with a cut-off frequency of 5 Hz; see Figure 2.

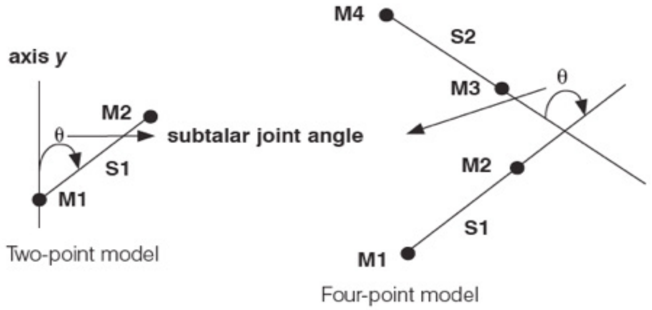

Figure 2 – Mathematical models of two and four points for calculation of subtalar pronation [2].

Maximum subtalar pronation and W_{int}. The predicted W_{int} was expressed as J/kg of body mass per unit distance travelled (m) and was associated with gait pattern modifications using the following formula [22]:

$$Wint = SF \cdot s \cdot \left(1 + \left(\frac{DF}{1 - DF} \right)^2 \right) \cdot q \quad (1)$$

in which *SF* is the stride frequency (Hz), *s* is the average progression velocity (m/s), *DF* is the duty factor, and *q* is a compound dimensionless term accounting for the inertial properties of the limbs and the mass partitioned between the limbs and the rest of the body (= 0.10 at gradient gaits) [23].

Statistical analysis. Data are expressed as mean ± SD. The data normality was verified using the Shapiro-Wilk test. As the results showed symmetrical behaviors, the Student's T-test was applied to dependent samples to compare the mean values of the W_{int} and the maximum subtalar pronation of both feet and in both mathematical conditions. One-way repeated-measures ANOVA was applied to compare the maximum values of subtalar pronation for each one of the gradients adopted. Significance at $p \leq 0.05$ was adopted for all statistical tests, and the statistical package used was the Statistical Package for the Social Sciences (SPSS) version 20.0.

Results

Analysis of the maximum values of subtalar pronation of both feet found no significant differences between the values of each foot regardless of the mathematical method used. Similar results were reported by Wit et al. [17] and Tartaruga et al. [6]. Consequently, the behavior of the right leg (dominant) of each subject was chosen for analysis. The mean mass of the shoe used in the sample was 210.2 grams, with a standard deviation of ± 86.1 grams.

Significant differences were found between W_{int} values of each gradient. However, no significant differences were observed in the maximum values of subtalar pronation between gradients in both mathematical method adopted, see Table 1.

Table 1 – Mean and standard deviation (SD) values of the variables internal mechanical work (W_{int}) and maximum subtalar pronation calculated with two and four anatomical reference points, at different gradients, of 16 trained male long-distance runners

gradients	1%	5%	10%	15%
W_{int} ($J.kg^{-1}.m^{-1}$)	0.54 ± 0.10	0.55 ± 0.10^{a}	0.58 ± 0.10^{ab}	0.61 ± 0.08^{abc}
2 points(°)	3.4 ± 1.8	3.1 ± 1.9	2.6 ± 1.7	2.5 ± 1.9
4 points(°)	8.0 ± 3.2*	7.9 ± 3.1*	7.6 ± 3.5*	7.3 ± 3.5*

Note: Asterisks represent statistically significant differences between the mathematical methods (i.e., 2 and 4 points); letters represent statistically significant differences compared with 1% (a); 5% (b) and 10% (c) gradients. $p < 0.05$.

Discussion

This study investigated the influence of positive gradients on internal mechanical work and maximum subtalar pronation at a submaximal running speed. The findings show W_{int} is impacted by gradient, but gradient does not influence the behavior of the subtalar joint during submaximal running irrespective of the mathematical model adopted. These results corroborate the studies by Minetti et al. [24] and Oliveira et al. [7].

According to Minetti et al. [24], W_{int} is an important component of the total mechanical work of running. In this study, W_{int} remained nearly constant at all downhill gradients, but increased at positive gradients. These changes in W_{int} parallel the changes recorded in the stride frequency. The lack of change in W_{int} at negative gradients suggests W_{int} has little influence on the optimal gradient. In addition, W_{int} is, by definition, formed from equal positive and negative components at all gradients [25]. The reduced dependence of W_{int} on speed during running compared with walking [26] is due to the flight time, which allows limbs to move more slowly in the swing phase in running during a progression run. In our study, the W_{int} increased at positive gradients at a submaximal running speed. These findings corroborate those of Minetti et al. [24]. The sum of W_{int} and W_{ext} [11, 12] is the total mechanical work (W_{tot}, in $J \cdot kg^{-1} m^{-1}$), and energy expenditure is reported at between 40% and 70% [27], with intraindividual variation between 3% and 11% [28].

However, no significant differences in the maximum values of subtalar pronation between gradients were observed despite the different values recorded according to the mathematical model used. These differences may be related to the movement at the segment S2, which is influenced by the rotation movements along the longitudinal axis and the translation movements of the tibia [2], in its turn influenced by internal tibial rotation as reflected in the second mathematical model, which uses four reference points (Wit et al. [17]). According to McClay and Manal [29], the internal rotation of the tibia is one of the main causes of subtalar pronation and contributes significantly to its absolute value. Likewise, the pronation action of the foot causes internal rotation of the tibia and of the femur, followed by the rotation of the entire leg [30]. A tibial rotation of 11.1° might entail dorsiflexion of the posterior part of the foot of 18.7°, which poses a higher risk of injury to the hip, knee and ankle. According to Snook [31], when repeated excessively, the internal rotation of the tibia can result in hyperpronation of the subtalar joint and, therefore, several osteoarticular complications. However, scholars have noted that physical condition and professional experience are significant variables affecting good running technique and thus the likelihood of developing subtalar hyperpronation [32, 33]. In our study, hyperpronation values were not observed.

The causes of lower limb pathologies also appear to result from the impact forces that overburden the pronation mechanism, posing a risk to the articular structures. When we observe hyperpronation of the subtalar joint, it is very probably associated with a strong impact that occurs during the foot-ground contact phase given that pronation is a mechanism that attenuates the impact resulting from the foot's contact with the ground, and consequently offers osteoarticular protection [17]. Study by Gottschall and Kram [34] confirms that impact forces are more influenced by variations in negative gradient than in positive gradient as locomotion in negative gradients requires greater use of elastic energy. In this study, the running speed was kept constant and at a comfortable rate, which was probably insufficient to cause changes in the impact force values and, consequently, changes in articular behavior. This result demonstrates the importance of running speed in the behavior of maximum subtalar pronation, as previously demonstrated by Oliveira et al. [7] (although Oliveira et al. [7] did not make mechanical evaluations (e.g. W_{int})). This study demonstrates that W_{int} is influenced by gradient, but gradient does not influence the behavior of the subtalar joint during submaximal running irrespective of the mathematical model adopted .

Some authors described the importance of the intensity of effort in the behavior of the biomechanical aspects of locomotion. For example, the preference for prescribing moderate intensity exercise rather than vigorous exercise reflects a body of research reporting a greater number of injuries caused by running than by walking. The American College of Sports Medicine (ACSM, 2011) states that, "Walking and moderate-intensity physical activities are associated with a very low risk of musculoskeletal complications, whereas jogging, running, and competitive sports are associated with increased risk of injury" [35, 36, 37]. However, an important distinction must be made. Walking and running differ in mode, not just in intensity. Running has a flight phase between steps, resulting in the runner striking the ground with greater force than a walker does [38]. Swain et al. [38] propose that the aerobic intensity of running is not responsible for the increased risk of musculoskeletal injuries; rather, this increased risk is due to impact forces. Moreover, mode selection can separate aerobic intensity from impact forces, an important possibility to consider when interpreting our results. In this study, we adopted different positive gradients undertaken at the same running speed, e.g. each subject ran at a comfortable speed at all gradients. Despite the increase in effort intensity confirmed by the W_{int} values, the maximum subtalar pronation values remained constant, regardless of the mathematical models adopted. Thus, this study recommends running on a treadmill on an inclined surface and at a constant speed as the ideal exercise choice. This approach does not affect maximum subtalar pronation and is, thus, unlikely to result in greater orthopedic stress when compared with running at high speeds on a horizontal plane.

Conclusion

The results of this study show that, applying any of the two mathematical models, gradient does not influence the maximum subtalar pronation during submaximal running, i. e., the maximum subtalar joint is not influenced by gradient but, probably, by physiological intensity. However, the W_{int} of running and consequently the intensity of effort are impacted by positive gradients. Incline treadmill running at a constant speed has been demonstrated to be an excellent choice of exercise as it causes no changes to the maximum subtalar pronation and consequently is unlikely to cause greater orthopedic stresses than is found when running at high speeds on a horizontal plane. This finding indicates that this form of running is safe and effective in periodization training. In terms of further studies, it is suggested that additional investigation of the influence of W_{ext} and the type of footwear on energy cost and of the maximum subtalar pronation in other conditions would be beneficial.

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References

1. Apte S, Plooij M, Vallery H. Influence of body weight unloading on human gait characteristics: a systematic review. J Neuroeng Rehabil. 2018;15(1):53.
2. Tartaruga MP, Cadore EL, Alberton CL, Nabinger E, Tartaruga LAP, Ávila AOV, et al. Comparison of protocols for determining the subtalar joint angle. Acta Ortop Bras. 2010;18(3):122-6.
3. Peltz CD, Haladik JA, Hoffman SE, McDonald M, Ramo NL, Divine G, et al. Effects of footwear on three-dimensional tibiotalar and subtalar joint motion during running. J Biomech. 2014;47(11):2647-53.
4. Takabayashi T, Edama M, Yokoyama E, Kanaya C, Inai T, Tokunaga Y, et al. Changes in Kinematic Coupling Among the Rearfoot, Midfoot, and Forefoot Segments During Running and Walking. J Am Podiatr Med Assoc. 2018;108(1):45-51.
5. Klingman RE, Liaos SM, Hardin KM. The effect of subtalar joint posting on patellar glide position in subjects with excessive rearfoot pronation. J Orthop Sports Phys Ther. 1997;25(3):185-91.
6. Tartaruga LAP, Tartaruga MP, Black GL, Coertjens M, Ribas LR, Kruel LFM. Comparison of the subtalar joint angle during submaximal running speeds. Acta Ortop Bras. 2005;13(2):57-60.
7. Oliveira VM, Detoni GC, Ferreira C, Portela BS, Queiroga MR, Tartaruga MP. Influence of slope on subtalar pronation in submaximal running performance. Acta Ortop Bras. 2013;21(3):163-6.
8. Margaria R. Sulla fisiologia e specialmente sul consumo energetico della marcia e della corsa a varia velocita ed inclinazione del terreno. Att Acc Naz Lincei. 1938;7:299-368.
9. Margaria R, Cerretelli P, Aghemo P, Sassi G. Energy cost of running. J Appl Physiol. 1963;18:367-70.
10. Davies CT, Sargeant AJ, Smith B. The physiological responses to running downhill. Eur J Appl Physiol Occup Physiol. 1974;32(3):187-94.

11. Cavagna GA, Kaneko M. Mechanical work and efficiency in level walking and running. J Physiol. 1977;268(2):467-81.

12. Tartaruga MP, Brisswalter J, Mota CB, Alberton CL, Gomenuka NA, Tartaruga LAP. Mechanical work and long-distance performance prediction: the influence of allometric scaling. J Hum Kinet. 2013;38:73-82.

13. Cavagna GA. Symmetry and asymmetry in bouncing gaits. Symmetry. 2010;2:1270-321.

14. Buczek FL, Cavanagh PR. Stance phase knee and ankle kinematics and kinetics during level and downhill running. Med Sci Sports Exerc. 1990;22(5):669-77.

15. Iversen JR, McMahon TA. Running on an incline. J Biomech Eng. 1992;114(4):435-41.

16. Ferrandis R, García AC, Ramiro J, Hoyos JV, Vera P. Rearfoot motion and torsion in running: the effects of upper vamp stabilizers. J Appl Biomech. 1994;10(1):28-42.

17. Wit BD, Clercq DD, Lenoir M. The effect of varying midsole hadness on impact forces and foot motion during foot contact in running. J Appl Biomech. 1995;11(4):395-406.

18. Williams KR, Cavanagh PR. Relationship between distance running mechanics, running economy, and performance. J Appl Physiol. 1987;63(3):1236-45.

19. Siri WE. Body composition from fluid spaces and density: analysis of methods. 1961. Nutrition. 1993;9(5):480-91.

20. Jackson AS, Pollock ML. Generalized equations for predicting body density of men. Br J Nutr. 1978;40:497-504.

21. Ellestad MH, Allen W, Wan MC, Kemp GL. Maximal treadmill stress testing for cardiovascular evaluation. Circulation. 1969;39(4):517-22.

22. Minetti AE. A model equation for the prediction of mechanical internal work of terrestrial locomotion. J Biomech. 1998;31(5):463-68.

23. Nardello F, Ardigò LP, Minetti AE. Measured and predicted mechanical internal work in human locomotion. Hum Mov Sci. 2011;30(1):90-104.

24. Minetti AE, Ardigò LP, Saibene F. Mechanical determinants of the minimum energy cost of gradient running in humans. J Exp Biol. 1994;195:211-25.

25. Minetti AE, Ardigò LP, Saibene F. Mechanical determinants of gradient walking energetics in man. J Physiol. 1993;472:725-35.

26. Minetti AE, Saibene F. Mechanical work rate minimization and freely chosen stride frequency of human walking: a mathematical model. J Exp Biol. 1992;170:19-34.

27. Keir DA, Zory R, Boudreau-Lariviere C, Serresse O. Mechanical efficiency of treadmill running exercise: effect of anaerobic-energy contribution at various speeds. Int J Sports Physiol Perform. 2012;7(4):382-9.

28. Morgan DW, Baldini FD, Matin PE. Day-to-day stability in running economy and step length among well-trained male runners (abstract). Int J Sports Med. 1987;8:242.

29. McClay I, Manal K. Coupling parameters in runners with normal and excessive pronation. J Appl Biomech. 1997;13(1):109-24.

30. Roper JL, Doerfler D, Kravitz L, Dufek JS, Mermier C. Gait Retraining From Rearfoot Strike to Forefoot Strike does not change Running Economy. Int J Sports Med. 2017;38(14):1076-82.

31. Snook AG. The relationship between excessive pronation as measured by navicular drop and isokinetic strength of the ankle musculature. Foot Ankle Int. 2001;22(3):234-40.

32. Silva RS, Ferreira AL, Veronese LM, Serrão FV. Forefoot varus predicts subtalar hyperpronation in young people. J Am Podiatr Med Assoc. 2014;104(6):594-600.

33. Hagen M, Lemke M, Lahner M. Deficits in subtalar pronation and supination proprioception in subjects with chronic ankle instability. Hum Mov Sci. 2018;57:324-31.

34. Gottschall JS, Kram R. Ground reaction forces during downhill and uphill running. J Biomech. 2005;38(3):445-52.

35. Garber CE, Blissmer B, Deschenes MR, Franklin BA, Lamonte MJ, Lee IM, et al. American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. Med Sci Sports Exerc. 2011;43(7):1334-59.

36. Poston WS, Haddock CK, Heinrich KM, Jahnke SA, Jitnarin N, Batchelor DB. Is High-Intensity Functional Training (HIFT)/CrossFit Safe for Military Fitness Training? Mil Med. 2016;181(7):627-37.

37. Dos'Santos T, Thomas C, Comfort P, Jones PA. The Effect of Angle and Velocity on Change of Direction Biomechanics: An Angle-Velocity Trade-Off. Sports Med. 2018;48(10):2235-53.

38. Swain DP, Kelleran KJ, Graves MS, Morrison S. Impact Forces of Walking and Running at the Same Intensity. J Strength Cond Res. 2016;30(4):1042-9.

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